Memorandum

To:	James Cashwell
From:	Peter Thompson, John Rand, C.G
CC:	Michael Murphy., Rod Pendleton C.G.
Ref:	DAPL Extraction Pilot Study Performance Evaluation Report
Subject:	Supplemental Water Level and Hydraulic Analysis February 5, 2015

This memorandum provides additional evaluation and hydraulic analysis of water level data collected during the DAPL Extraction Pilot Test (Pilot Test) conducted at the Olin Chemical Superfund Site, in Wilmington, MA. USEPA requested that Olin provide plots of hydrogeologic data collected during the Pilot Test. The data has been represented in a series of calculation sheets, tables, and figures, which are attached hereto. We have provided the detailed discussion below to accompany the data and to assist with USEPA's review.

Background

Water level data was collected during the Pilot Test from the DAPL extraction well (EW-1) and from within three ports at two adjacent multilevel piezometers (ML-1 and ML-2), MP-2 and GW-43DR. Water levels were collected before and after pumping rate step changes and at periodic intervals during the test. The primary use of this data has been to document the magnitude of water level drawdown, the existence of vertical groundwater flow components (gradients) in vicinity of EW-1 during pumping, and to demonstrate the gravimetric flow of DAPL along the bottom of the bedrock pool toward the extraction well. The extraction well is installed at the bottom of the DAPL pool with a five-foot screen and sand pack extending two feet above the screen. The well screen and sand pack penetrate only about one-half of the DAPL thickness, and about one-quarter of the full saturated thickness of soil. The well design is intended to allow removal of DAPL from the bottom of the bedrock depression by gravity drainage. The Pilot Test intentionally evaluated pumping rates that were anticipated to be similar to and higher than the rate of gravity drainage which was estimated to be on the order of 0.5 gallons per minute (gpm). It was expected (and confirmed) that pumping at rates higher than 0.5 gpm would result in downward movement of DAPL toward the well screen from the DAPL interface due to the imposition of vertical gradients toward the well screen.

Pumping at rates less than or equal to 0.5 gpm causes all DAPL flow to the well to be from gravity drainage which would theoretically result in a uniform lowering of the DAPL interface over the

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entire DAPL pool. Pumping at rates in excess of 0.5 gpm would initiate a non-uniform lowering of the DAPL interface by inducing vertical movement of DAPL downward toward the well screen. This downward vertical movement of DAPL would be accompanied by intrusion of the overlying diffuse layer material and overlying groundwater into the DAPL surrounding the well screen and potential dispersion of DAPL constituents above the DAPL/Diffuse Layer interface due to convective mixing. The radial distance at which this process occurs is assumed to be equivalent to the hydraulic radius of influence of the extraction well at a given pumping rate. Since DAPL is an aqueous fluid, it is expected that variations in vertical permeability in the soil would result in a gradual and progressive dilution of DAPL within that radius of influence rather than a uniform displacement of the DAPL interface.

The proposed mechanism for the observed DAPL drawdown therefore has two components:

1) Uniform Vertical Pool Lowering (due to gravity drainage), and
2) Non-Uniform DAPL Displacement Surrounding the Extraction Well (due to vertical gradients and dilution induced by pumping at a rate exceeding gravity drainage).

Analysis Objective and Methodology

The objectives of this hydraulic analysis include:

- Developing an estimate of the radius of hydraulic influence from pumping as a basis to estimate the volume of aquifer around the extraction well that was affected by displacement of DAPL through intrusion of overlying waters and dilution, and

- Developing an estimate of the volume of DAPL removed by gravity drainage compared to DAPL displacement by overlying waters.

<u>Radius of Influence</u>

The water level data was reviewed and plotted in a series of hydrographs (Attachment A) for EW-1 and the deepest ports in ML-1 and ML-2 (Port 4) which are closest in elevation to the screened interval of EW-1. Although there is a vertical component of flow to the well, use of the lower elevation port data is more consistent with the assumptions of horizontal flow to a well screen required by most pumping test data analysis methods. This data was reviewed and data points were selected that appeared to represent maximum drawdown values for the highest pumping rate (2 gpm).

A distance drawdown plot was then constructed to estimate aquifer Transmissivity (T) and the Coefficient of Storage (S) for the 2.0 gpm pumping step. T was also calculated for the 1.0 gpm data set and the result was similar, though a little higher. The 2.0 gpm data set represents the maximum pumping stress and is considered the better of the two data sets. Methods used are described on page 237 of *Groundwater and Wells (Driscoll, 1986).* The distance drawdown plot also allows for an estimate of the radius of influence (ROI). Methods are also available based on ratios of pumping rates to approximate expected drawdown and ROI at different pumping rates (Driscoll, page 240). These plots are presented in Attachment B. Based on a saturated thickness of 40 feet, the computed transmissivity (2,296 gpd/ft) was used to calculate hydraulic conductivity (7.7 feet/day). Assuming two days to achieve steady state, this T value would yield a Storage Coefficient (S) of 0.14.

$S=0.3Tt/r_0^2$
Where T = transmissivity in gpd/ft,
t = time in days
r_0 = radius of influence in feet

As a secondary check to the ROI calculation in Driscoll, the unsteady state Theis equation for confined aquifers was used to predict the magnitude drawdown expected at 100 feet at 24 hours using these computed hydraulic conductivity and storage coefficient values (Attachment C). Although the system is not confined, the steady state solutions for confined and unconfined aquifers have the same form (Analysis and Evaluation of Pumping Test Data, Kruseman and Ridder, 1983) and either are appropriate where drawdown is small in relation to the aquifer thickness, as is the case here. The plots in Attachment C indicate the Theis prediction suggest little to no measureable drawdown at 100 feet. Thus the ROI prediction of 100 feet at 2 gpm appears to be reasonable.

DAPL Volume Attributed to Gravity Drainage

Table 1 presents an evaluation of the contribution of DAPL from Gravity Drainage and by Displacement and Dilution. Figures 1 through 3 illustrate these concepts through presentation of conceptual cross sections before and at the end of DAPL extraction. (Figure 1 indicates the section orientation, Figure 2 the DAPL pool prior to DAPL extraction and Figure 3 the DAPL pool at the end of DAPl extraction). The DAPL system operating time was approximately 404 days and a total of 596,727 gallons of DAPL and diluted DAPL were removed (with the diluted DAPL being due to higher pumping rates). An estimate of the degree of dilution is provided in Table 1. Of the total DAPL and diluted DAPL removed for transport and disposal (T&D), approximately 477,369 gallons is believed to represent the undiluted, in-place DAPL volume.

If the gravity drainage rate was in the range of 0.5 to 0.6 gpm over the 404 day period, approximately 349,000 gallons of DAPL (73%) represents gravity drainage to the well (based on upper range of 0.6 gpm). This would also contribute about 1 foot or more of decline in DAPL elevation across the entire DAPL pool.

DAPL Volume Attributed to Displacement and Dilution Around the Extraction Well

As indicated earlier, the hydraulic ROI inferred from water level data is approximately 100 feet. This represents the maximum distance we would expect displacement and dilution of DAPL from pumping in excess of gravity drainage rates. With a hydraulic conductivity of 7.7 feet/day, and a horizontal gradient of 1 foot per 100 (0.01) and a porosity of 0.3, the calculated travel distance over 404 days of pumping is approximately 104 feet, which is consistent with this 100 foot ROI estimate (7.7 feet/day*0.01*404 days /0.3 = 103.7 feet).

Table 1 presents a calculation of a right square cone volume equivalent to a height of 5.5 feet (DAPL drawdown due to over pumping) and a radial distance of 100 feet. Assuming a porosity of 0.3, this volume would represent 129,245 gallons (27%) of the total in-place (undiluted) DAPL that was removed.

Conclusions

The hydrogeologic data collected as part of the DAPL extraction pilot test indicates that a 0.5-gpm extraction rate is the most efficient and appropriate rate of the three rates tested for potential long-term success of this system. DAPL extraction from a single well at 0.5 gpm allows gravity-based DAPL recovery without unacceptable draw down, potential precipitation, or convective mixing. DAPL recovery at extraction rates greater than 0.5 gpm causes drawdown that results in DAPL dilution and entrainment of overlying groundwater and diffuse material, and non-gravimetric DAPL recovery across a large portion of the DAPL pool. Based on hydraulic data collected, an estimate of 100 feet has been established for the hydraulic radius of influence of EW-1 pumped at 2 gpm (i.e the distance from the extraction well of groundwater contribution when pumping). Based on T&D records, and dilution of DAPL observed in EW-1 during pumping steps with 1.0 and 2.0 gpm rates, it is estimated the Pilot Test removed approximately 477,000 gallons of in-place, un-diluted DAPL. Approximately 73% of this volume was from gravity drainage at a rate somewhere between 0.5 and 0.6 gpm. The additional DAPL volume recovered in response to pumping at a rate greater than gravity drainage is accounted for in the aquifer volume at the top of the DAPL interface outward to the ROI of the extraction well. This volume represents material that was diluted by intrusion of overlying diffuse layer material and overlying groundwater into the DAPL surrounding the extraction well above the top of the well screen. The vertical and horizontal flow to the well screen at EW-1 controls the degree and extent of DAPL dilution which increases as the distance to the well decreases. Exceeding gravity flow of DAPL to the well by as much as a factor of 4 (2.0/0.5 gpm) does not appear to greatly increase the removal rate of in-place DAPL and comes with a penalty of dilution and, therefore, a situation where DAPL, diffuse material, and overlying groundwater are all being extracted and treated resulting in a much more inefficient and potentially damaging remedial process.

Tables

Table 1
Estimate of Volumetric DAPL Contribution
Supplemental Hydraulic Analaysis Memorandum

DAPL Specific Conductance and Dilution		
Period	**Average EW-1 Specific Conductance (umohs/cm)**	**Estimate of Dilution at EW-1**
0.5 gpm Step	>99,000	1
1.0 gpm Step	89,704	0.9
2.0 gpm step	69,452	0.7

DAPL Gallons			
Period	**T&D Volume**	**Estimate of Dilution at EW-1**	**In-Place DAPL Volume**
0.5 gpm Step	56,600	1	56,600
1.0 gpm Step	213,400	0.9	192,060
2.0 gpm step	326,727	0.7	228,709
Total T&D	596,727		477,369

Estimated Dilution Based on Specific Conductance data from EW-1
Total Days of Active Pumping 404

DAPL Sources / Contribution
1) Gravity Drainage
2) Displacement and Dilution

1) Gravity Drainage Contribution (assuming 0.5 to 0.6 gpm gravity flow)

0.5	gpm			0.6	gpm
404	days			404	days
290,880	Gallons			349,056	Gallons

Range	**290,880**	**to**	**349,056**	**Gallons**	**73%**

2) Displacement and Dilution (Volume Approximated by Right Cone)

$V = \pi r^2 h/3$

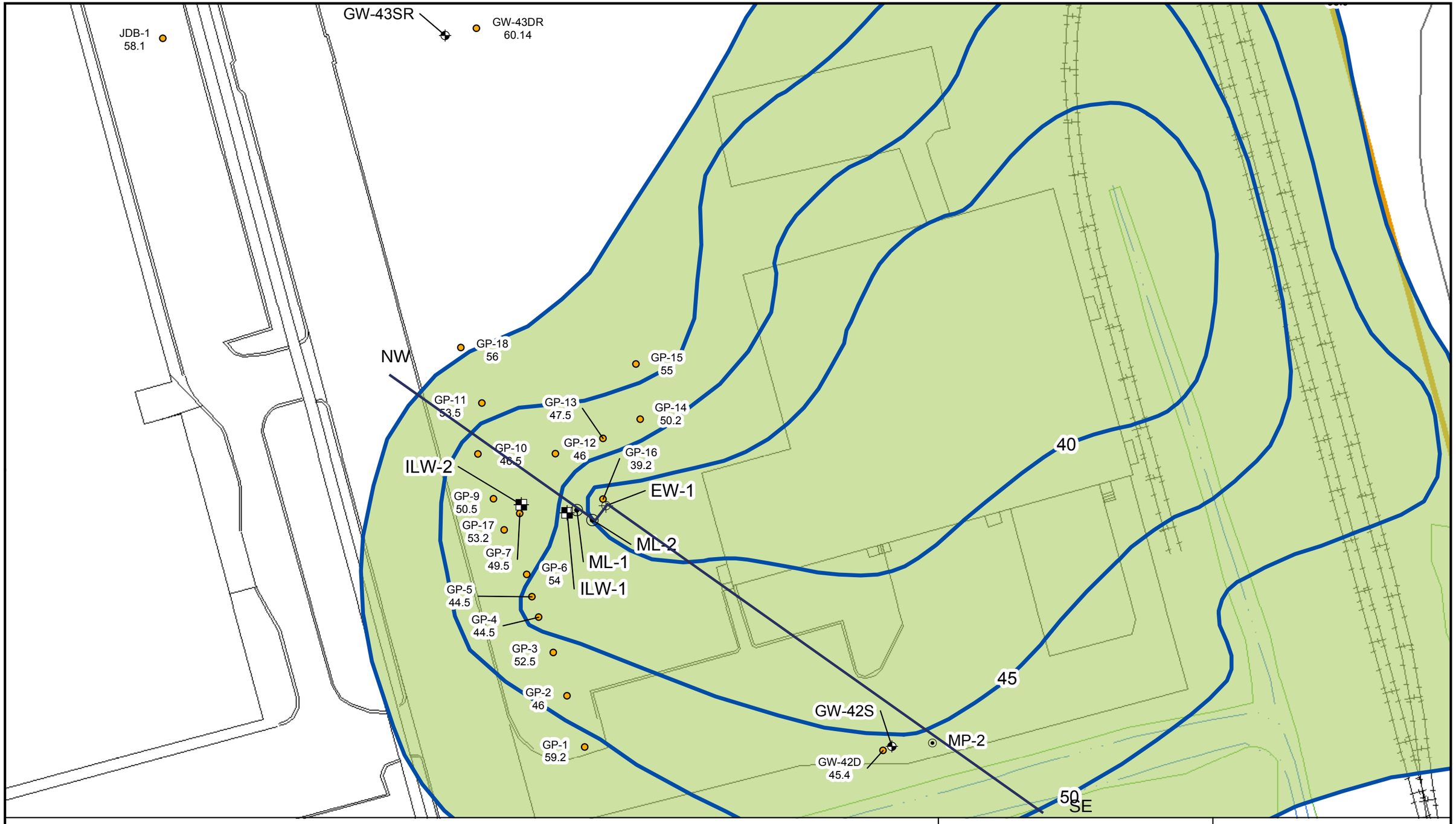
DAPL Drawdown	5.5	feet	
ROI = 100 feet	100	feet	
Porosity	0.3		
V=	57,596	Cubic Feet	
	430,818	Gallons	
Total Volume	**129,245**	**Pore Space Volume (Gallons)**	

Total Volume	**420,125**	**to**	**478,301**	**Gallons**	**27%**

6.5 feet Total DAPL Drawdown at EW-1
Assumes 5.5 feet of DAPL Drawdown due to Displacemnet and Dilution
Assumes 1.0 feet due to Uniform Lowering Due to Gravity Drainage

Prepared by: PHT 1/19/2015
Checked by: JBR 1/19/2015

Figures



Legend

- Monitoring Well Location
- Induction Logging Well
- Multi Level Well
- Extraction Well
- Updated Bedrock Contours
- Interpreted Extent of DAPL Off Property Below 55 ft Contour
- Exploration Confirming Bedrock Elevation
- Railroad
- Paved Road
- Unpaved Road
- Sidewalks
- Surface Water
- Trails
- Wetland Symbol
- Wetland Boundary
- 51 Eames St. Property Boundary

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N

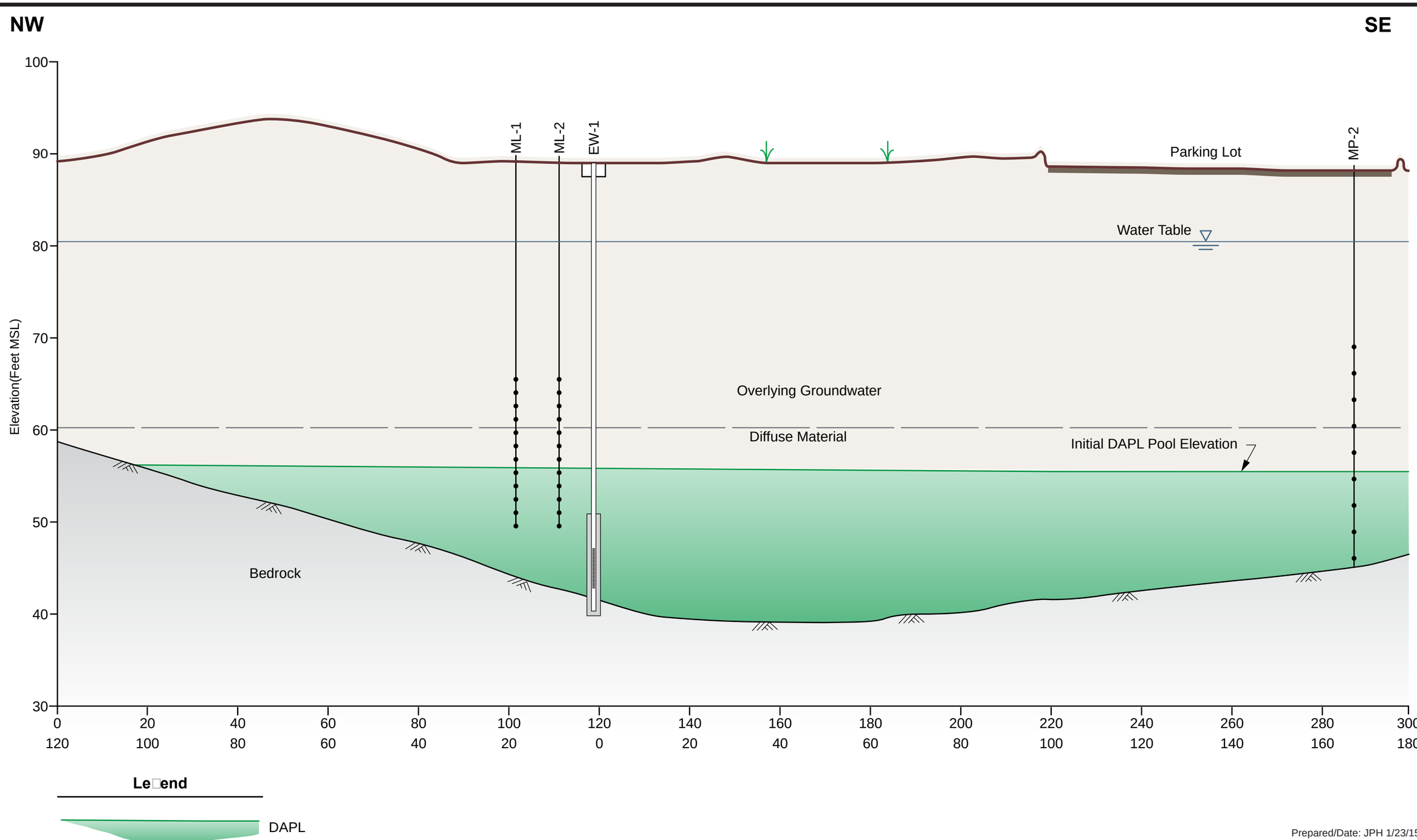
0 20 40 80 Feet

Figure 1
Location of NW-SE Conceptual Section Line

Olin Chemical Superfund Site
Wilmington, Massachusetts

Prepared by BJR | Checked by PHT

Document: P:\old_Wakefield_Data\projects\OLIN\Wilmington\GIS\MapDocuments\DAPL_Recalc_11X17_LS.mxd PDF: P:\old_Wakefield_Data\projects\OLIN\Wilmington\GIS\Figures\Figure 2-1 - Location of Extraction Well and Monitoring Well Network.pdf 11/4/2014 3:18 PM brian.roden



Prepared/Date: JPH 1/23/15
Checked/Date: PHT 1/23/15

6107150016	511 Congress Street Suite 200 Portland, Maine	Figure 2 Conceptual Section Through DAPL Before DAPL Extraction Pool Olin Chemical Superfund Site Wilmington, Massachusetts

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NW

SE

Elevation(Feet MSL)

100
90
80
70
60
50
40
30

ML-1
ML-2
EW-1
MP-2

Parking Lot

ROI = 100 FT
(R_o)

R_o = 100 FT

0.5 gpm
1.0 gpm
2.0 gpm

Static

Water Level Drawdown
at 0.5, 1.0 and 2.0 gpm

ROI @ 100'

Overlying Groundwater

Diffuse Material

Initial DAPL Pool Elevation

Final DAPL Pool Elevation

Bedrock

0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300
120 100 80 60 40 20 0 20 40 60 80 100 120 140 160 180

Legend

DAPL Gravity Drainage

Uniform decline in DAPL pool
due to gravity drainage

Intrusion of diffuse overlying groundwater

DAPL volume contributed by displacement
and dilution @ Q > 0.5 gpm

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Figure 3
End of Pumping Conceptual Section Through DAPL
Pool Illustrating Sources of DAPL to EW-1
Olin Chemical Superfund Site
Wilmington, Massachusetts

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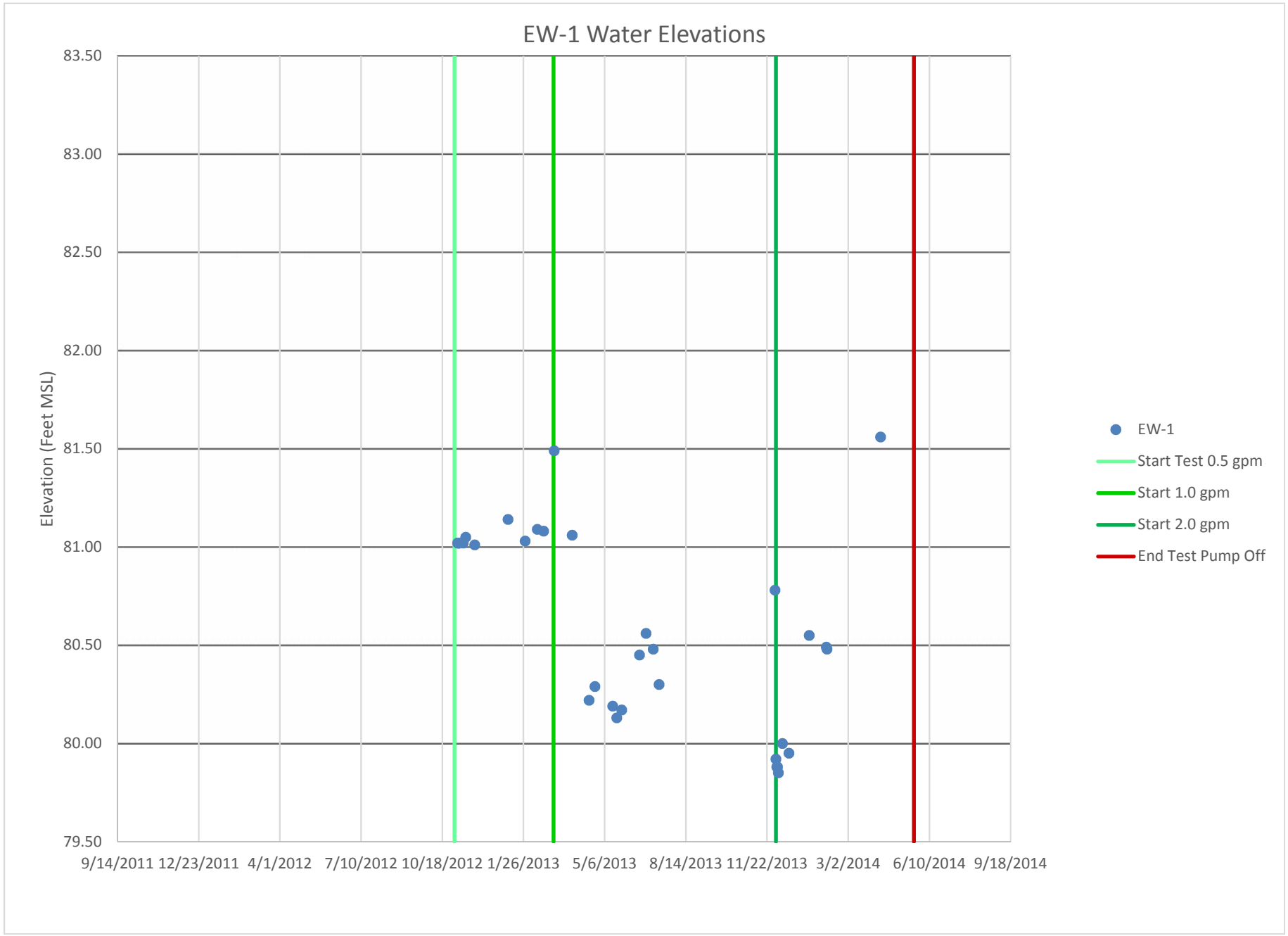
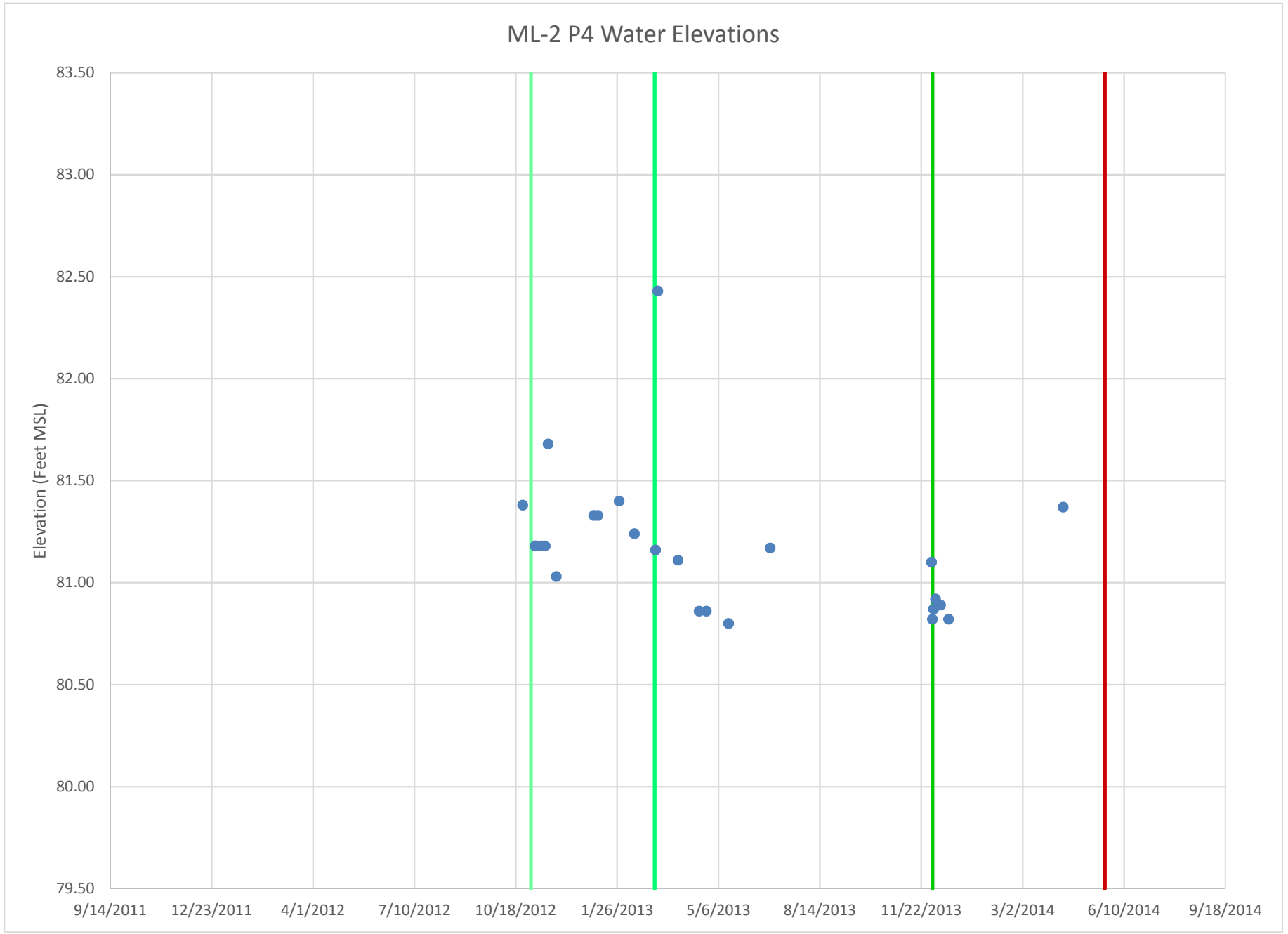
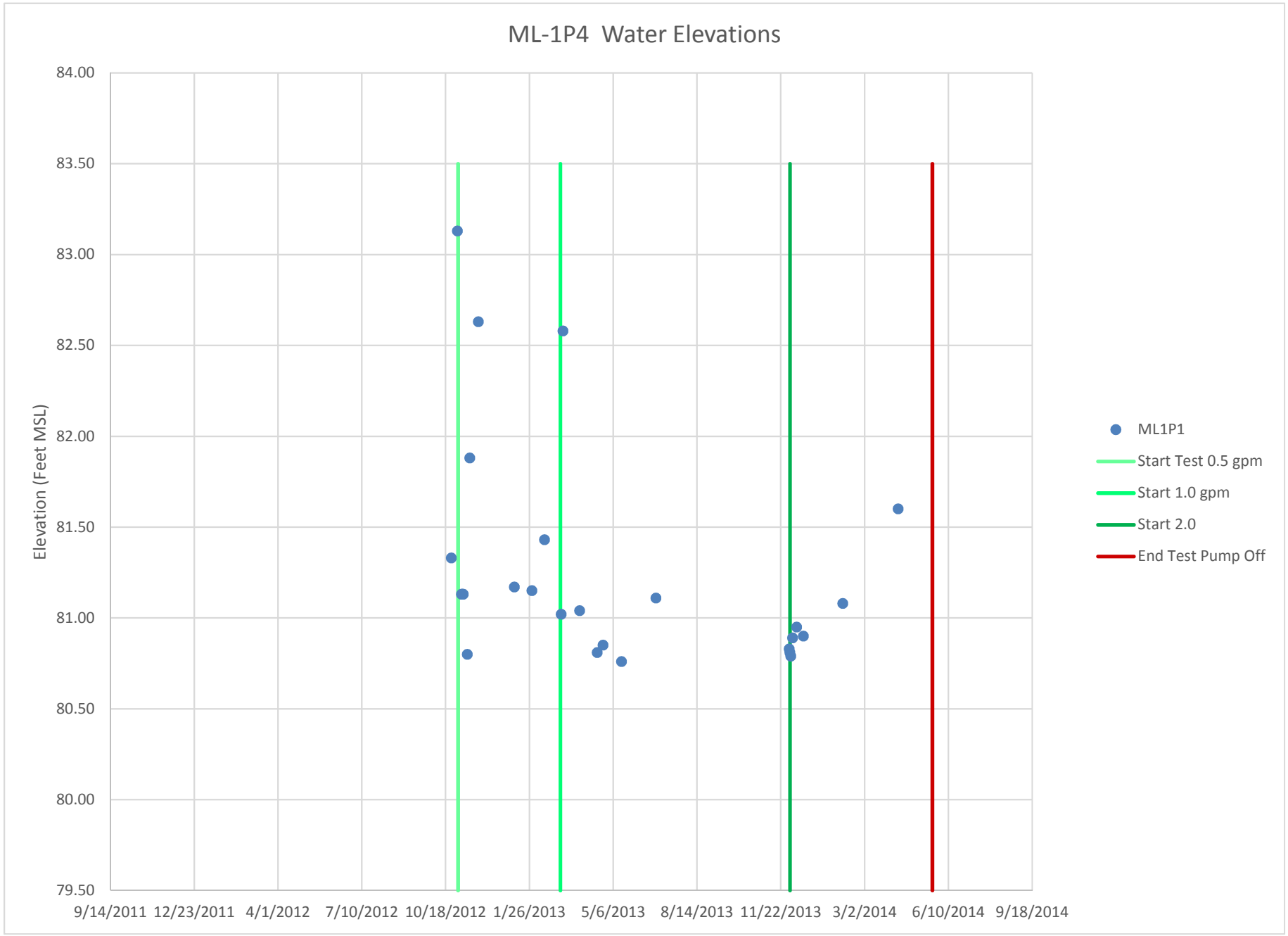
Attachment A

Water Level Hydrographs


EW-1 Water Elevations
Elevation (Feet MSL)
83.50
83.00
82.50
82.00
81.50
81.00
80.50
80.00
79.50
9/14/2011
12/23/2011
4/1/2012
7/10/2012
10/18/2012
1/26/2013
5/6/2013
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
EW-1
Start Test 0.5 gpm
Start 1.0 gpm
Start 2.0 gpm
End Test Pump Off

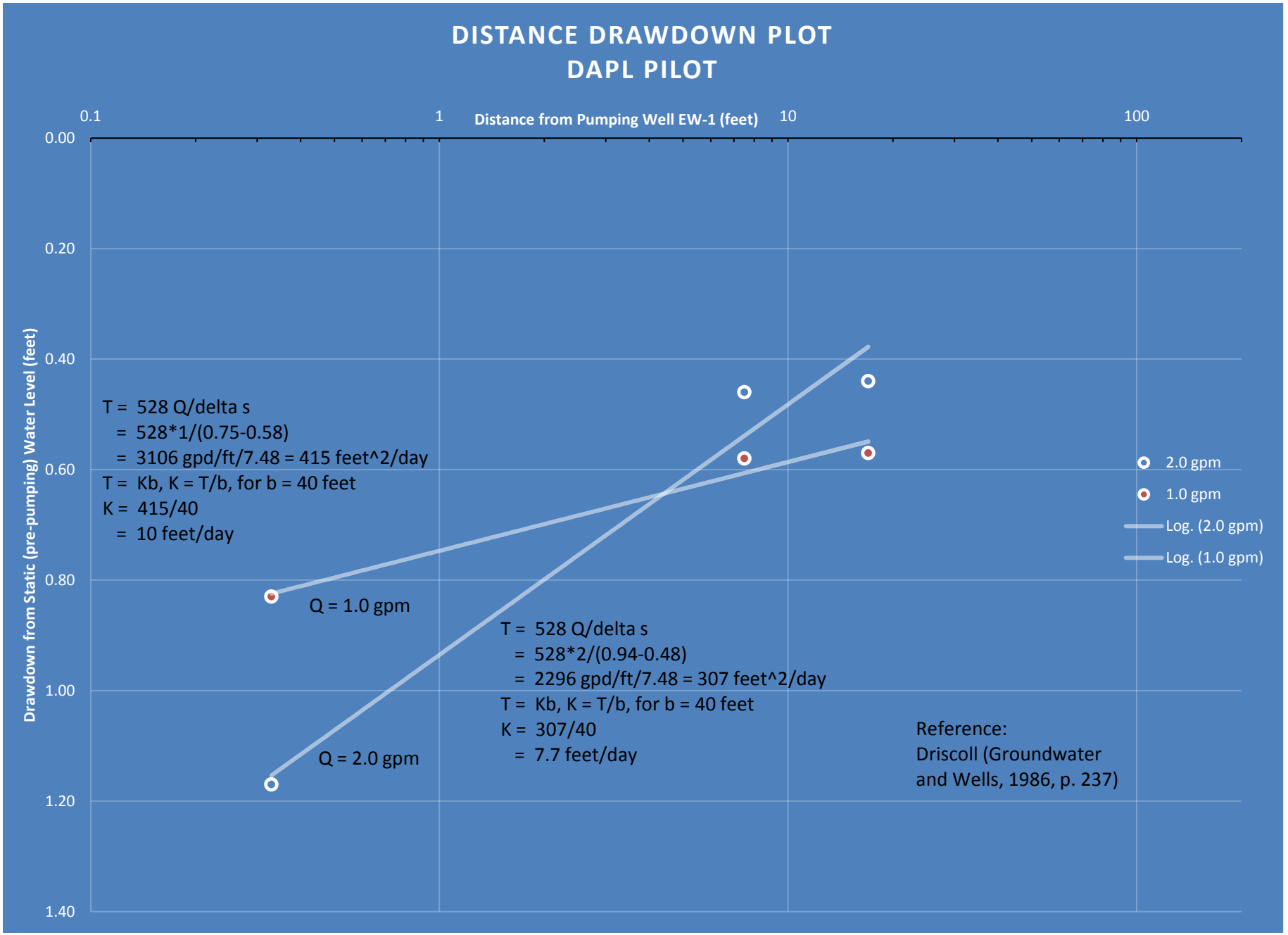

ML-2 P4 Water Elevations
Elevation (Feet MSL)
83.50
83.00
82.50
82.00
81.50
81.00
80.50
80.00
79.50
9/14/2011
12/23/2011
4/1/2012
7/10/2012
10/18/2012
1/26/2013
5/6/2013
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014

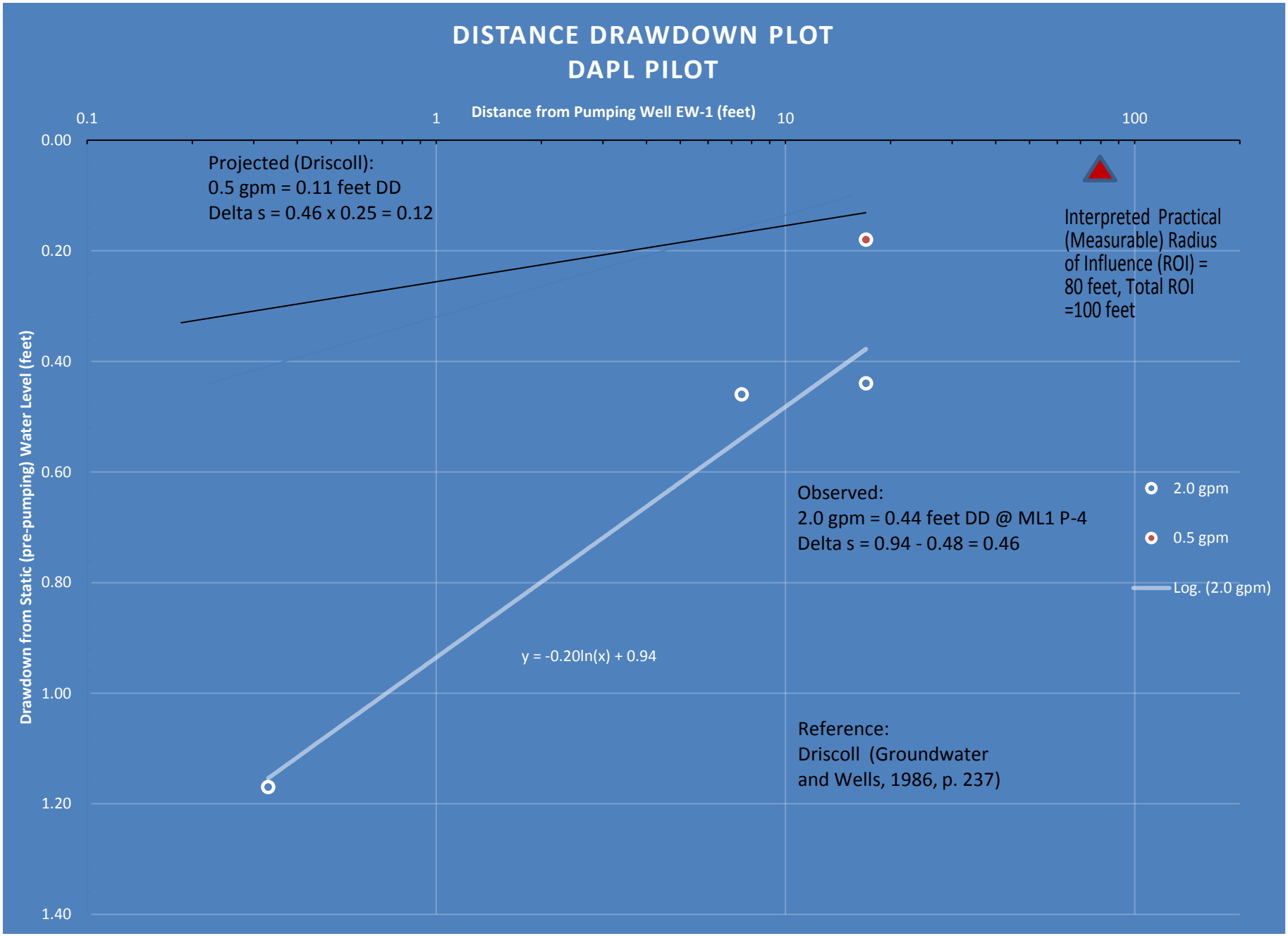

ML-1P4 Water Elevations
Elevation (Feet MSL)
84.00
83.50
83.00
82.50
82.00
81.50
81.00
80.50
80.00
79.50
9/14/2011
12/23/2011
4/1/2012
7/10/2012
10/18/2012
1/26/2013
5/6/2013
8/14/2013
11/22/2013
3/2/2014
6/10/2014
9/18/2014
ML1P1
Start Test 0.5 gpm
Start 1.0 gpm
Start 2.0
End Test Pump Off

Attachment B

Distance Drawdown Plots

Estimates of Transmissivity, Storage Coefficient and
R_0 (Radius of Influence)


DISTANCE DRAWDOWN PLOT
DAPL PILOT
0.1
1
Distance from Pumping Well EW-1 (feet)
10
100
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
Drawdown from Static (pre-pumping) Water Level (feet)
T = 528 Q/delta s
= 528*1/(0.75-0.58)
= 3106 gpd/ft/7.48 = 415 feet^2/day
T = Kb, K = T/b, for b = 40 feet
K = 415/40
= 10 feet/day
Q = 1.0 gpm
T = 528 Q/delta s
= 528*2/(0.94-0.48)
= 2296 gpd/ft/7.48 = 307 feet^2/day
T = Kb, K = T/b, for b = 40 feet
K = 307/40
= 7.7 feet/day
Q = 2.0 gpm
Reference:
Driscoll (Groundwater
and Wells, 1986, p. 237)
2.0 gpm
1.0 gpm
Log. (2.0 gpm)
Log. (1.0 gpm)


DISTANCE DRAWDOWN PLOT
DAPL PILOT
Distance from Pumping Well EW-1 (feet)
0.1
1
10
100
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
Drawdown from Static (pre-pumping) Water Level (feet)
Projected (Driscoll):
0.5 gpm = 0.11 feet DD
Delta s = 0.46 x 0.25 = 0.12
Interpreted Practical (Measurable) Radius of Influence (ROI) = 80 feet, Total ROI =100 feet
Observed:
2.0 gpm = 0.44 feet DD @ ML1 P-4
Delta s = 0.94 - 0.48 = 0.46
2.0 gpm
0.5 gpm
Log. (2.0 gpm)
y = -0.20ln(x) + 0.94
Reference:
Driscoll (Groundwater and Wells, 1986, p. 237)

Attachment C

Theis Distance Drawdown Prediction

at

K= 7.7 feet day

S=0.14

t= 1 day

Drawdown Prediction for Confined Aquifers, Theis(1935)

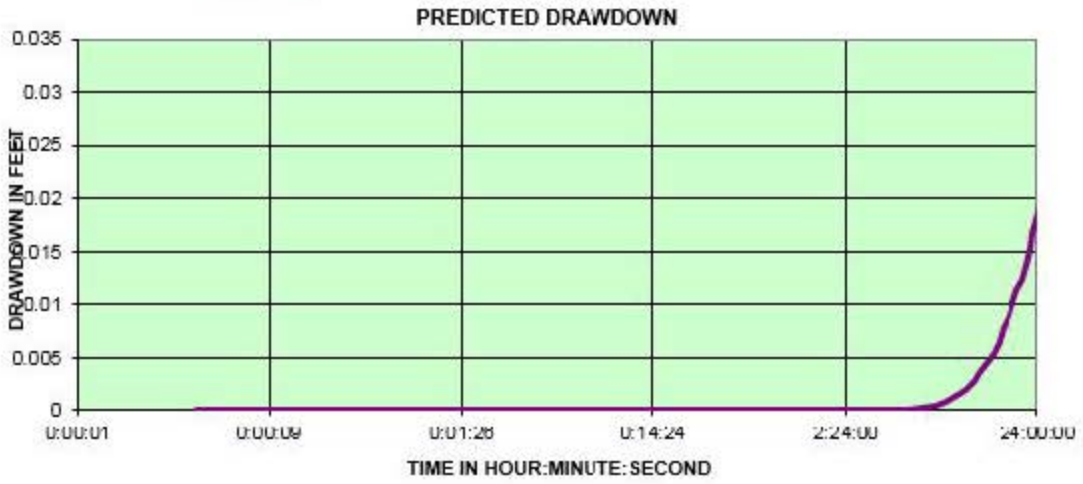
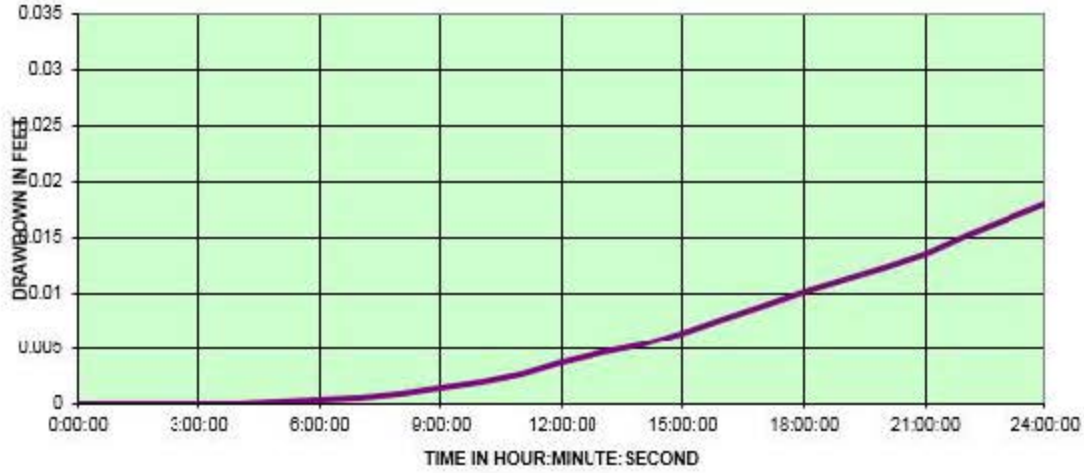
Input Data for prediction of drawdo...

Hydraulic conductivity, K, ft/day	7.7
Aquifer Thickness, b, ft	40
Storage Coefficient, S	1.40E-01
Pumping Rate, GPM	2
Distance from well, ft	100

K: 0.01 0.1 1 10 100 1000

S: 1.00E-06 1.00E-05 1.00E-04 1.00E-03 1.00E-02 1.00E-01 1.00E+00

Equation used in prediction

$$s = \frac{Q(W(u))}{4\pi T} \qquad u = \frac{r^2 S}{4Tt}$$

s is drawdown, W(u) is the well